Forecasting of Solar Particle Event Doses Using Bayesian Inference

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Abstract—This work reports the use of Bayesian inference methods to make forecasts of dose-time profiles due to solar particle event proton fluxes using dose and dose rate values from early in the evolution of the event. Predicted profiles for absorbed dose in water are presented for the September 24, 2001, November 4, 2001, and November 22, 2001 solar particle events. Dose-time profiles are modeled with non-linear regression techniques that assume Weibull and Gompertz growth curves. Predictions are implemented by Markov Chain Monte Carlo sampling techniques. Results for the September 24, 2001 event under-predict actual asymptotic dose and suggest a refinement of the categorization methodology. Predictions for the November 2001 events provide good agreement with the actual dose-time profiles. This work provides encouraging results towards the development of a real-time, event-triggered, advanced warning system.

1. Introduction

Current solar particle event (SPE) models predict cumulative fluence [1,2,3,4,5,6], worst-case fluence [5,7], and peak flux [8] over a given mission duration. The Feynman model [4] is useful for design of components and associated long-term degradation but is limited in terms of energy range and does not address the temporal evolution of individual events. The Xapsos et al. models for worst case fluence and peak flux [5,7,8], again, are useful for spacecraft design when considering a worst case event or the expected peak flux for a given mission duration. The CREME96 model [9] predicts radiation effects on spacecraft electronics using a worst day model, a worst week model, and a peak flux model. All models are based on average SPE fluxes for the October 19, 1989 SPE. The CREME96 model provides a worst-case environment for component design, but offers no predictions for an on-going event. While all of these models are useful tools for spacecraft component design, none address the question of the real-time space environment or the temporal evolution of a given event. Indeed, due to the conservative assumptions of the above models, one might over-design spacecraft shielding and components, rather than allowing for temporary, mitigative actions. Furthermore, these models do not predict the potential consequences to humans for an on-going event.

The National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC) provides space weather alerts and warnings as well as daily and weekly operational products. Alerts and warnings are used to alert users to observed conditions or impending occurrences. Daily operational products include a report and forecast of solar and geophysical activity. The daily report provides a summary of the previous 24 hours and a forecast of solar activity for the next 3 days. Space weather scales for solar radiation storms generally describe biological, satellite operations and other systems effects as well as the flux level of particles with energies ≥10 MeV. In this work, we consider the forecasting of dose, applicable to humans and electronics alike, due to SPE protons.

As there are no physical or empirical models, to date, which correlate solar observable precursors to doses resulting from the occurrence of SPEs, an event-triggered system, which uses dose and/or dose rate information from early in the evolution of an SPE may provide the best opportunity for space mission operators to implement mitigative strategies such as crew rotation, emergency shielding, or delay/cancellation of operations. Dose-time profiles have a non-linear temporal dependence, usually modeled as a non-linear, sigmoidal growth curve. These models lend themselves to the prediction of future doses given data from early in the event. Previous work [10,11] utilized either an innovative, sliding-time delay neural network or Bayesian inference methods and calculated dose and/or dose rate

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values to make predictions of asymptotic dose and dose/dose rate time profiles for SPEs. Using Bayesian inference methods, as implemented by Markov Chain Monte Carlo sampling techniques, we present forecasted dose-time profiles for the three largest (in terms of particles with energies >10 MeV) SPEs of 2001: (1) September 24, 2001, (2) November 4, 2001, and (3) November 22, 2001, using only dose and dose rate values from the first few hours of the event.

The operational implementation of this methodology would utilize onboard instruments to mark the beginning of an event and onboard dosimeters to provide real-time dose and dose rate values as input into software implementing our empirical model.

2. METHODOLOGY

The methodology used in this work was earlier reported by Neal and Townsend [11]. As before, dose rate data are used to initially categorize the SPE, and dose data are used to make inferences about model parameters and physical observables. The following sections provide a brief review of the principal components of this methodology.

Dose and Dose Rate Calculations

Since dose and dose rate data in deep space are unavailable for these events, surrogate dose and dose rate data are obtained by calculating them using measured proton fluxes. Differential and integral proton flux and fluence spectra were measured on the Geostationary Operational Environmental Satellite (GOES)-7 and GOES-8 for the NOAA SEC and provided to researchers via the NOAA SEC website. Five minute average flux histories are parameterized by an exponential rigidity (momentum per unit charge) function. Parameter values are used as input to the deterministic, coupled neutron-proton space radiation computer code, BRYNTRN [12], for transport of protons and their reaction products (protons, neutrons, H-2, H-3, He-3, and He-4) through aluminum shield material (1 g/cm^2). Dose and dose rates are the BRYNTRN code output. Previous work by the authors [13] demonstrated similar dose-time profiles for dose calculated in the lens of the eye, the blood forming organs, the skin, and water.

Bayesian Inference

Bayesian statistics may be characterized as a statistical methodology that requires the expression of uncertainty in hypotheses, parameters, and data as probability distributions. If H represents a hypothesis and D represents data, Bayes' Theorem may be stated as:

$$p(H \mid D) = \frac{p(D \mid H)\, p(H)}{p(D)} \qquad (1)$$

where P(H|D) is a probabilistic statement about H after observing data (posterior distribution); P(D|H) is the likelihood of the data given the hypothesis; P(H) is a probabilistic statement of belief about H before observing data (prior distribution) ; P(D) is the marginal distribution of the data. If a hypothesis can be expressed as the parameter(s) of a given model,

$$p(\theta \mid D) = \frac{p(D \mid \theta)\, p(\theta)}{p(D)} \qquad (2)$$

Bayes' Theorem allows one to update the probabilistic beliefs about model parameters in a logical fashion, after observing new data. Individual (marginal) parameter posterior distributions require integration of the joint parameter posterior distribution over all other parameters.

While parameter distributions may have some physical significance, such as asymptotic dose, the thrust of this work requires prediction of physical observables, dose as a function of time. To make these predictions, the predictive density is calculated as

$$p(y_f \mid D) = \int p(y_f \mid \theta)\, p(\theta \mid D)\, d\theta \qquad (3)$$

where y_f represents some future observable. Forecasts of dose are made using the appropriate variable transformation and predictive distributions. As with the parameter distributions, dose predictions may be expressed as probability distributions rather than point estimates.

Markov Chain Monte Carlo

Markov Chain Monte Carlo (MCMC) methods provide a much-needed tool to perform the integrations necessary to calculate individual parameter posterior distributions as well as predictive distributions, as in (3) above, for physical observables. The most widely used MCMC simulation methods are the generalized Metropolis algorithm [14] and the Gibbs sampler [15].

A Markov chain is a stochastic process where given the present state, past and future states are independent

$$p(X_{t+1} \mid X_0, X_1, \ldots X_t) = p(X_{t+1} \mid X_t) \qquad (4)$$

The goal of MCMC simulation is to create a Markov process whose stationary distribution is the joint posterior

Table 1. Hierarchical Model Group Characteristics and SPE Members

Group Number	Asymptotic Dose Range (cGy)	Maximum Dose Rate (cGy-h^{-1})	SPE Members
1	500-5000	>40	July 14, 2000 March 23, 1991 November 8, 2000
2	100-500	10-40	October 19, 1989 September 29,1989 August 12, 1989
3	1-100	0.1-10	June 4, 1991 March 19, 1990 November 30, 1989
4	0-1	0-0.1	August 26, 1991 January 31, 1991 November 8, 1987

Table 2. Criteria for Categorization of New Events

Group Number	Maximum Dose Rate Within 5 Hours Into Event (cGy-h^{-1})
1	>15
2	0.1-15
3	0.05-0.1
4	0-0.05

distribution. This stationary distribution may then be sampled to provide an approximation to the posterior distribution of interest. It is necessary to determine if the simulation has indeed been run long enough to allow convergence to the stationary distribution. For this work, the BUGS (Bayesian Inference Using Gibbs Sampling) software package [16] was used to implement Bayesian methods of growth curve parameter inference. Examination of convergence diagnostics included with the BUGS package was used for convergence monitoring.

Empirical Models

Since no physical model exists to describe the generation, transport, and acceleration of particles associated with SPEs and no correlations between solar observables (e.g. sunspots) and dose-time profile parameters have been found to date, the authors investigated non-linear regression models which considered time as the sole regressor variable in Weibull and Gompertz growth curves. After review of historical SPE dose-time profile data, it was noted that SPE with large asymptotic dose exhibited relatively large maximum dose rates and relatively large initial dose rates. Initial dose rates are used to place individual SPE into groups. Table I presents group characteristics and previously analyzed SPE members. The third criterion, large initial dose rate, allows categorization of new events early in the evolution of the event. Table II presents criteria for categorization of new events. It is this grouping of similar SPE and the assumption that those SPE are drawn from a common population that allows the modeler to use hierarchical models.

Hierarchical, or multi-level, non-linear regression models were assumed for each of the four groups listed in Table I. The dose-time profile is assumed to follow a non-linear, sigmoidal growth curve, with two such functions considered:

$$D = D_\infty(1-\exp(-(\alpha t)^\gamma))) \qquad \textit{Weibull} \qquad (5)$$

$$D = \exp(\alpha - \beta\gamma^t) \qquad \textit{Gompertz} \qquad (6)$$

3. RESULTS

The following sections present results for dose-time profile predictions for the September 24, 2001, November 4, 2001, and November 22, 2001 SPEs. Three Markov chains of 100,000 iterations each were run in parallel for each dose-time profile prediction. Predicted dose-time profile curves use mean or median values for doses at each predicted time. It should be noted that the September 24, 2001 SPE data were added to the Group 2 data set for the November 4, 2001 SPE forecasts. Likewise, the November 4, 2001 SPE data were added to the Group 2 data set for the November 22, 2001 SPE forecasts. Bayesian inference methods provide a natural way to incorporate new SPE data into a given group's data set.

Forecasts for the September 24, 2001 SPE

The September 24, 2001 SPE began at 1215 Universal Time (UT). The associated halo coronal mass ejection (CME) was observed at 1030 UT. The observed dose rate exceeded the group 2 dose rate criterion (see Table 2) at one hour into the event. Predicted dose-time profiles are presented for two through six hours into the event. Figures 1 through 5 present dose-time profiles generated from Gompertz model predicted median values.

Forecasts for the September 24, 2001 SPE consistently under-predict the asymptotic dose value of 500 cGy with the prediction at six hours forecasting only 66% of the actual asymptotic dose. One may note that the six hour prediction is made when actual dose is only 1.6% of the asymptotic dose. Calculated dose rates early in the event place this event in group 2 while the asymptotic dose falls on the boundary of groups 1 and 2 (see Table 1). These results suggest the need for a further refinement of the Table 2 categorization criteria.

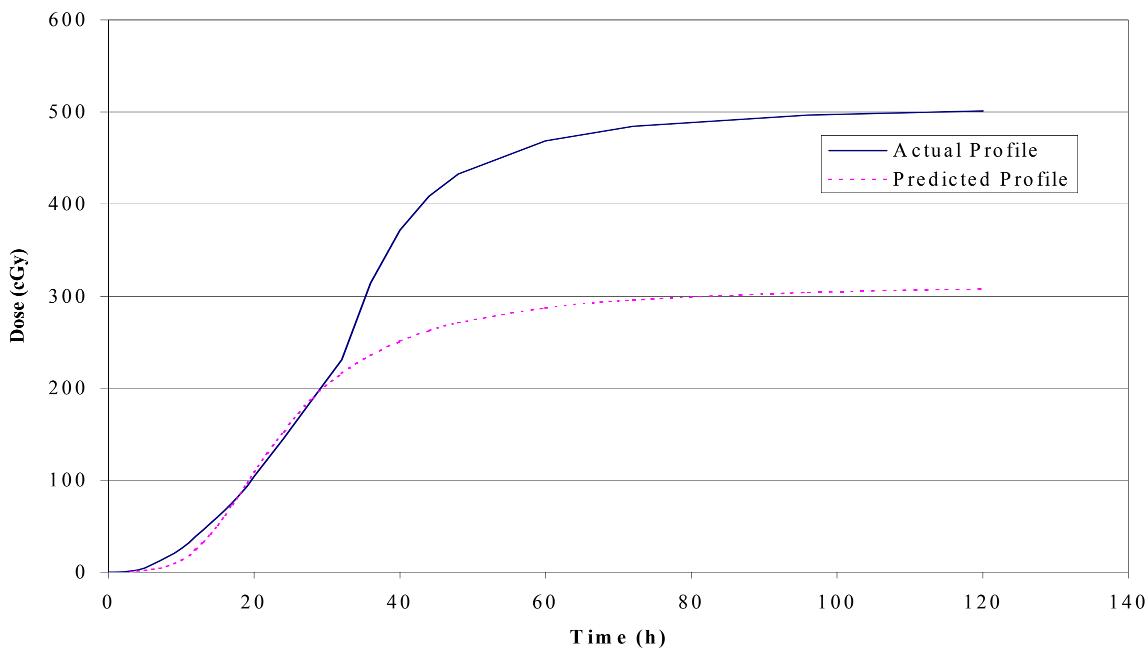

Figure 1. Predicted dose-time profile at 2 hours (or 0.1% of asymptotic dose) into September 24, 2001 SPE.

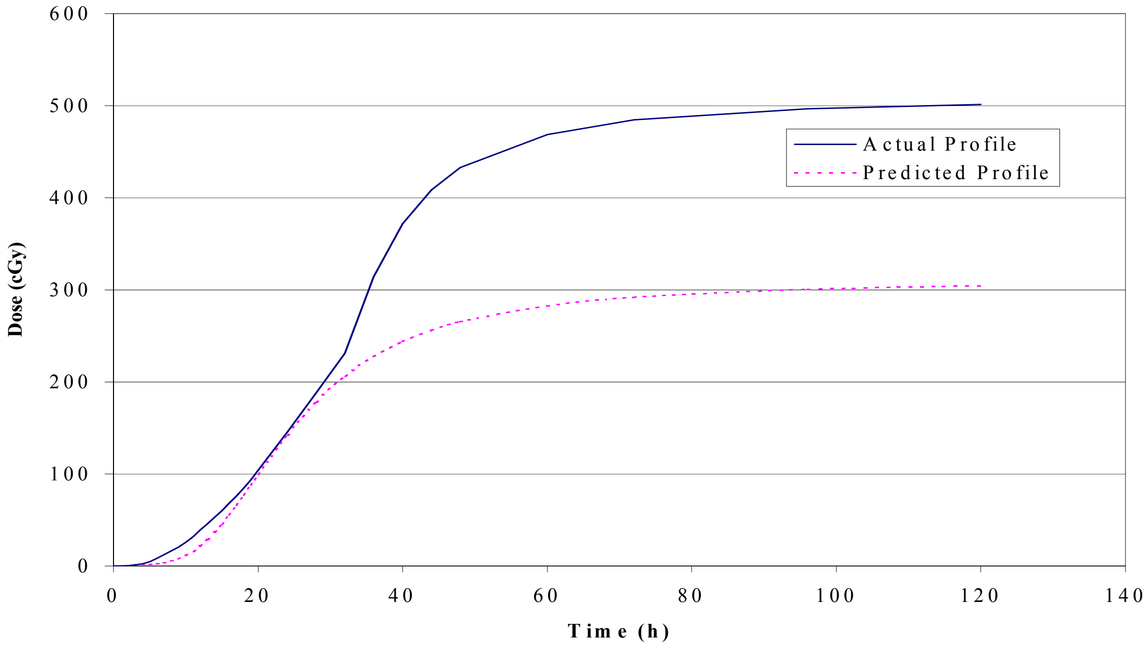

Figure 2. Predicted dose-time profile at 3 hours (or 0.2% of asymptotic dose) into September 24, 2001 SPE.

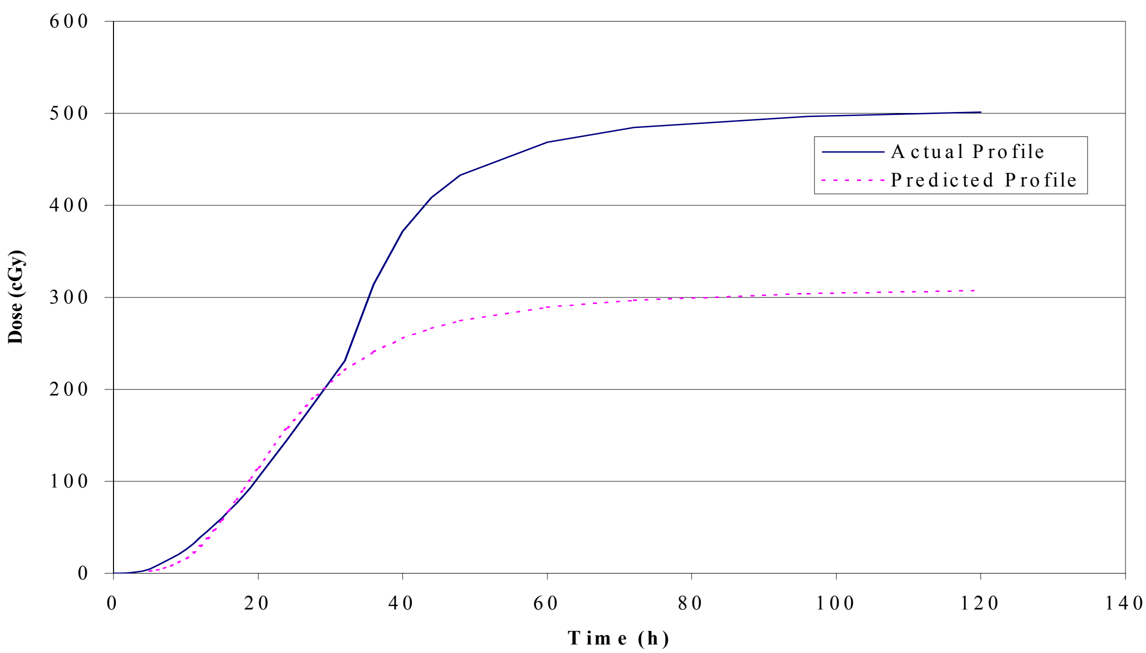

Figure 3. Predicted dose-time profile at 4 hours (or 0.4% of asymptotic dose) into September 24, 2001 SPE.

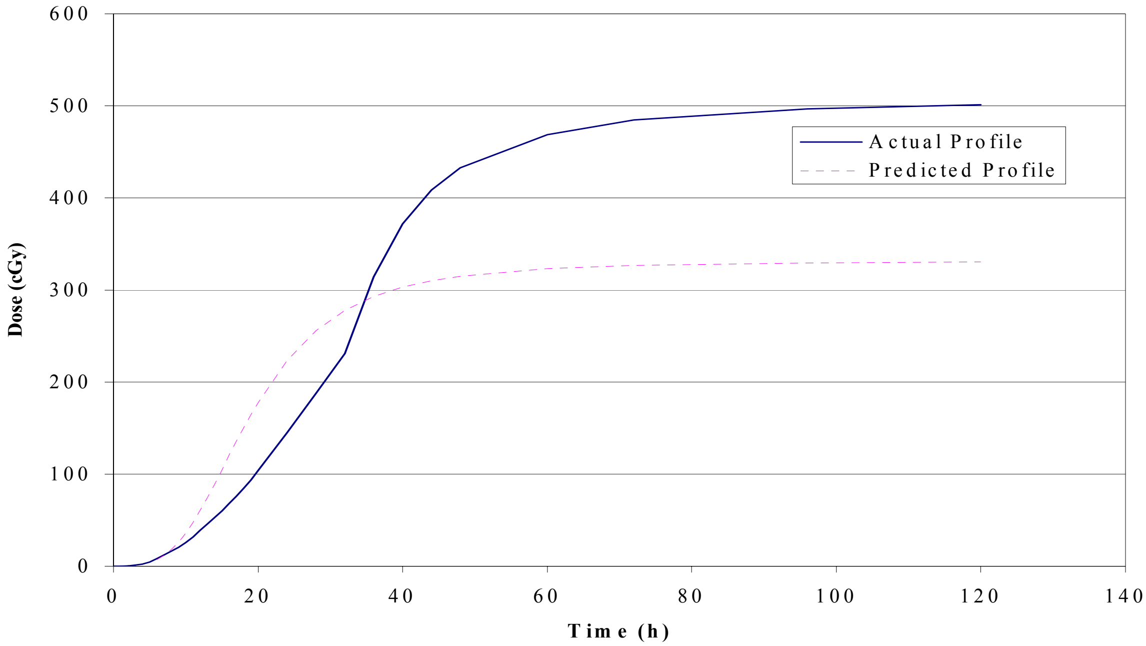

Figure 4. Predicted dose-time profile at 5 hours (or 0.9% of asymptotic dose) into September 24, 2001 SPE.

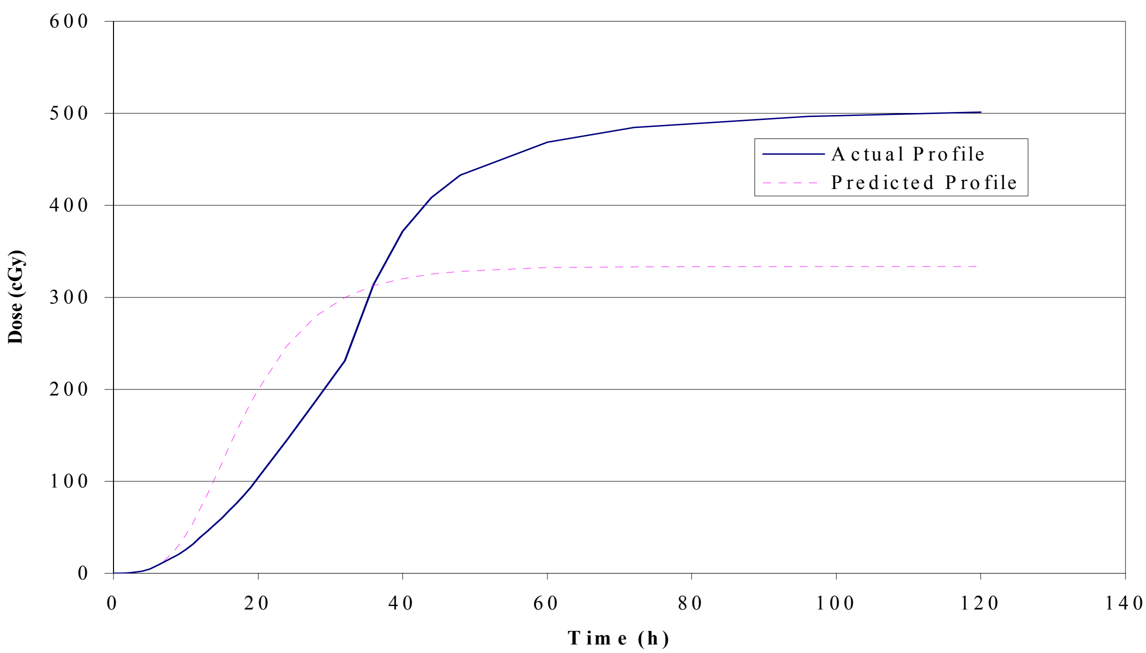

Figure 5. Predicted dose-time profile at 6 hours (or 1.6% of asymptotic dose) into September 24, 2001 SPE.

Forecasts for the November 4, 2001 SPE

The November 4, 2001 SPE began at 1705 UT. The associated halo CME was observed at 1635 UT. The observed dose rate exceeded the group 2 dose rate criterion (see Table 2) at one hour into the event. Predicted dose-time profiles are presented for two through six hours into the event. Figures 6 through 10 present dose-time profiles generated from Weibull model predicted mean values. Due to the arrival of an interplanetary shock at approximately 23 hours into the event, forecasts are made out to 24 hours into the event.

Forecasts for the November 4, 2001 SPE are quite good up to the arrival of the interplanetary shock. The six hour prediction forecasts 107% of the actual asymptotic dose with good agreement of the predicted and actual dose-time profiles.

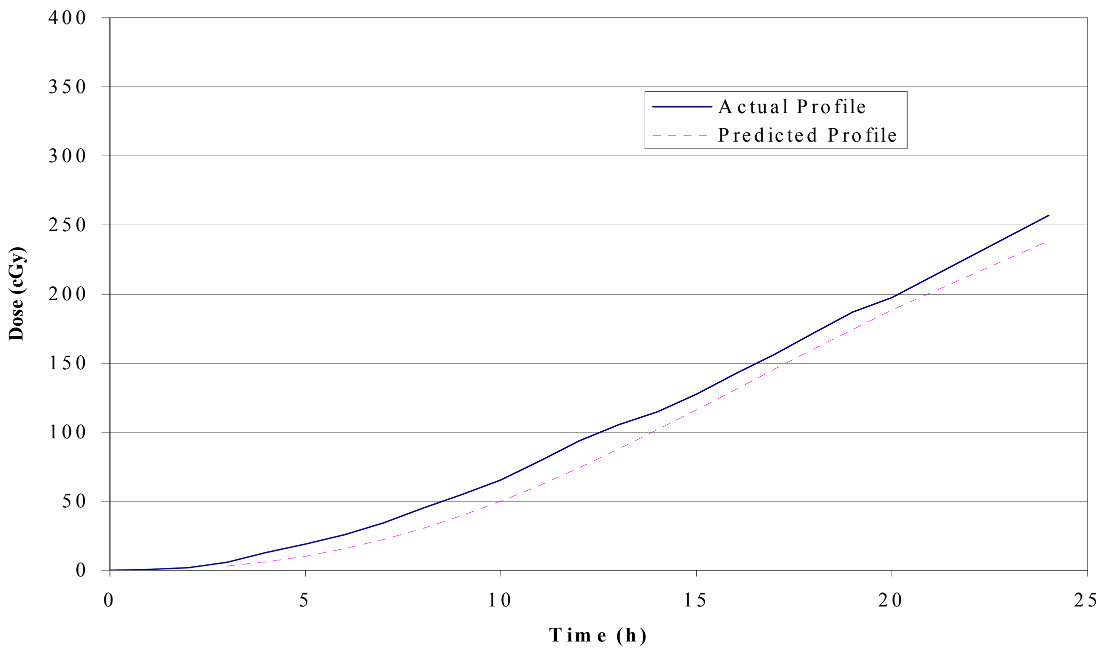

Figure 6. Predicted dose-time profile at 2 hours (or 0.7% of dose at 24 hours) into November 4, 2001 SPE.

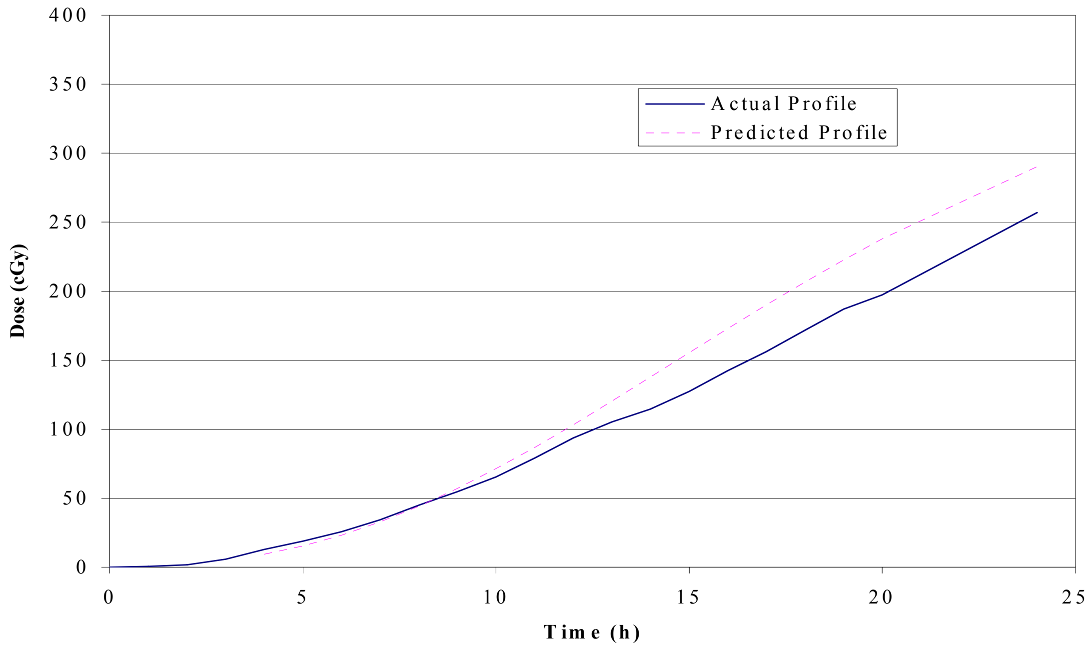

Figure 7. Predicted dose-time profile at 3 hours (or 2.3% of dose at 24 hours) into November 4, 2001 SPE.

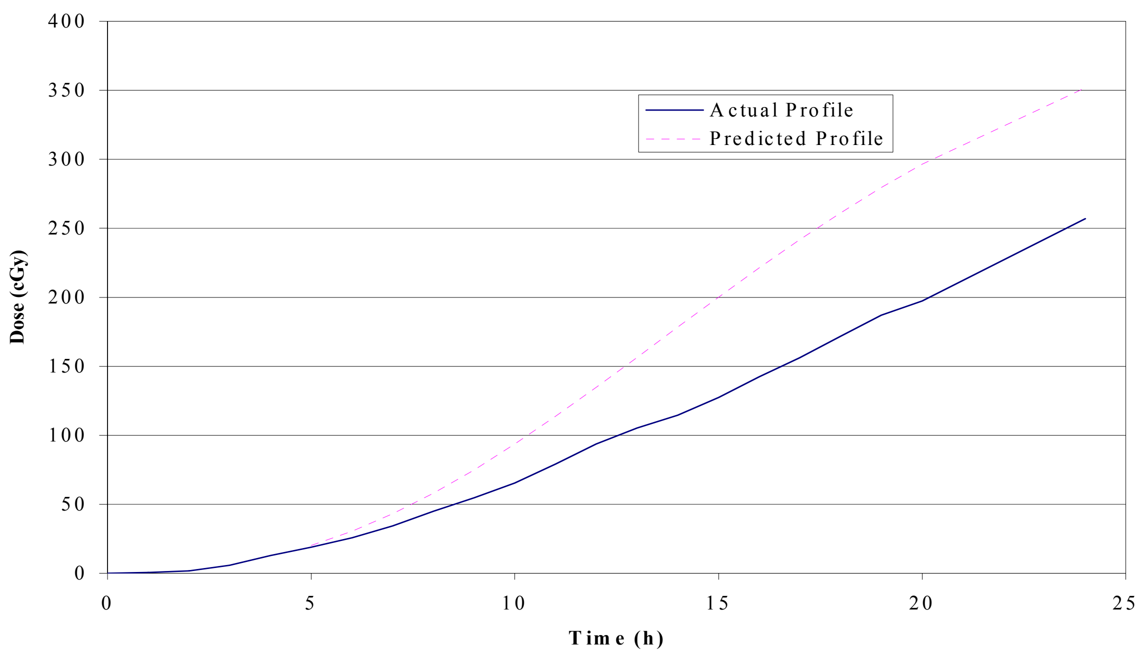

Figure 8. Predicted dose-time profile at 4 hours (or 5.1% of dose at 24 hours) into November 4, 2001 SPE.

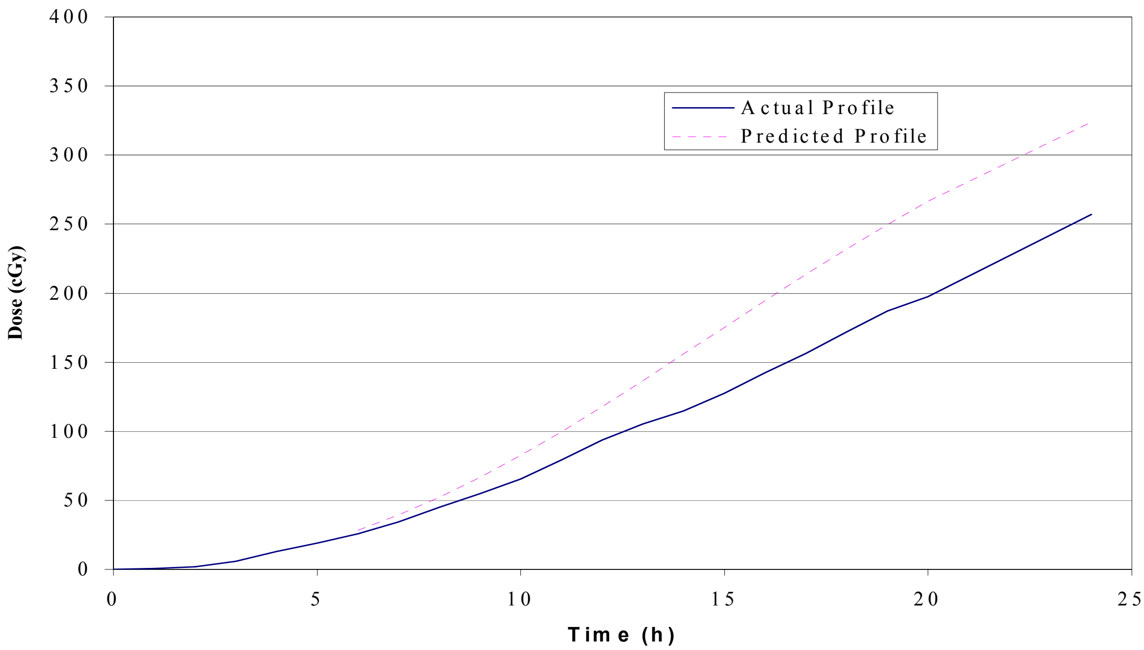

Figure 9. Predicted dose-time profile at 5 hours (or 7.4% of dose at 24 hours) into November 4, 2001 SPE.

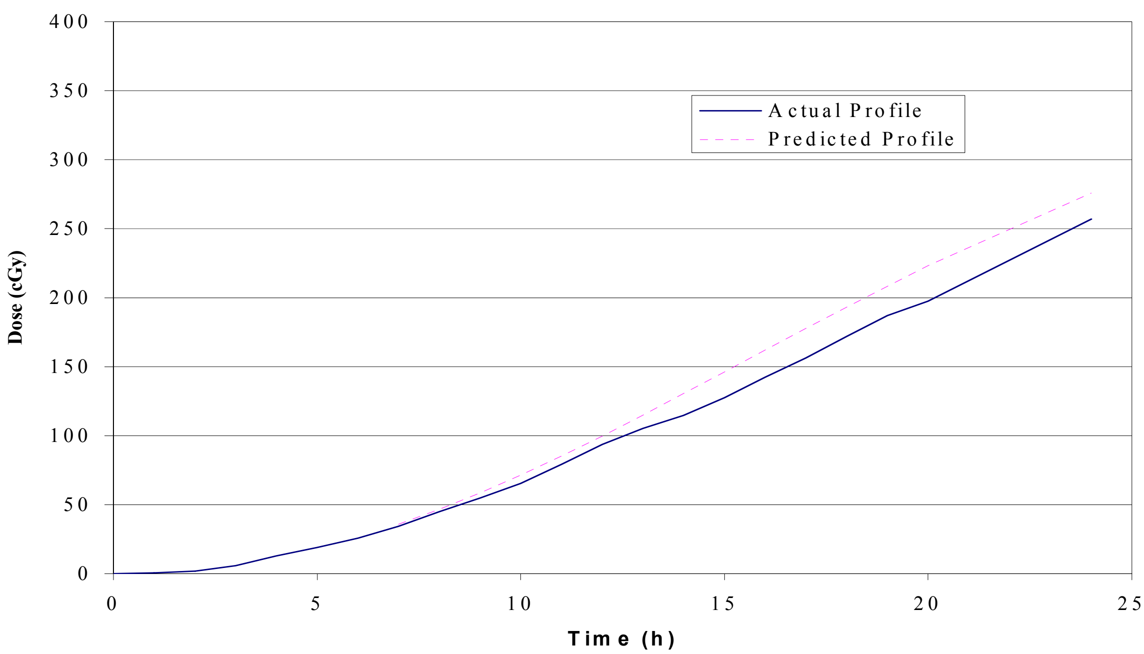

Figure 10. Predicted dose-time profile at 6 hours (or 10.0% of dose at 24 hours) into November 4, 2001 SPE.

Forecasts for the November 22, 2001 SPE

The November 22, 2001 SPE began at 2320 UT. The associated halo CME was observed at 2330 UT. The observed dose rate exceeded the group 2 dose rate criterion (see Table 2) at two hours into the event. Predicted dose-time profiles are presented for two through six hours into the event. Figures 11 through 15 present dose-time profiles generated from Gompertz model predicted mean values. Due to the arrival of an interplanetary shock at approximately 23 hours into the event, forecasts are made out to 24 hours into the event.

Forecasts for the November 22, 2001 SPE consistently underestimate actual dose values until the prediction at six hours. The predicted dose-time profile at six hours is quite good considering the forecast is made at 3% of the dose at 24 hours. The six hour prediction forecasts 129% of the actual asymptotic dose with good agreement of the predicted and actual dose-time profiles up to 16 hours followed by gradually increasing overprediction up to 24 hours.

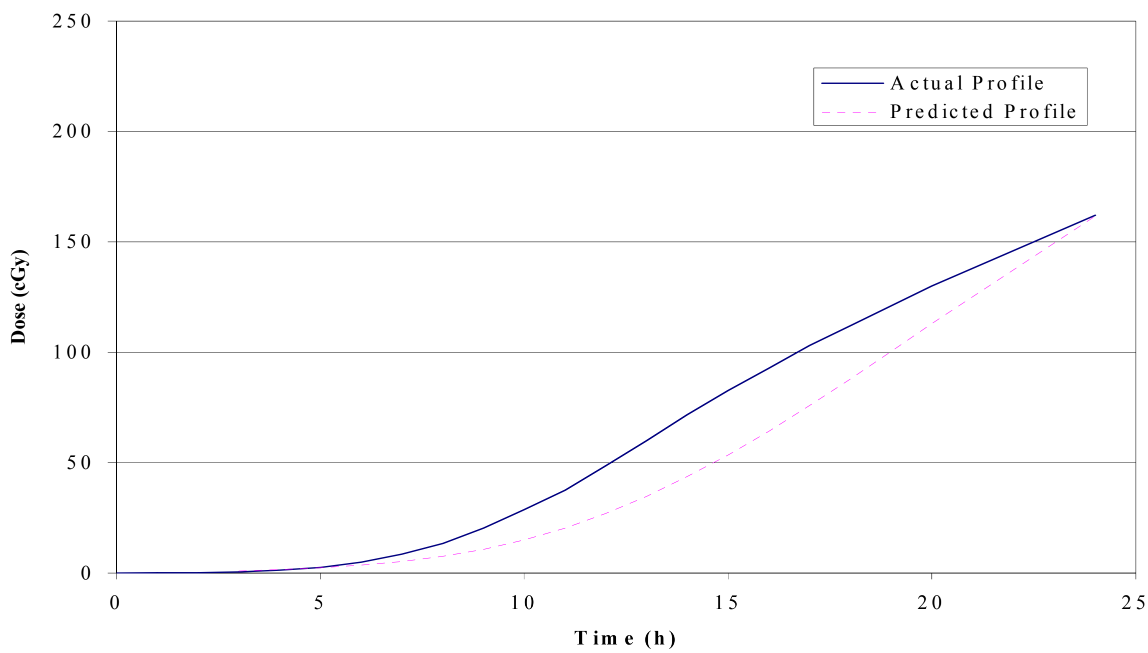

Figure 11. Predicted dose-time profile at 2 hours (or 0.1% of dose at 24 hours) into November 22, 2001 SPE.

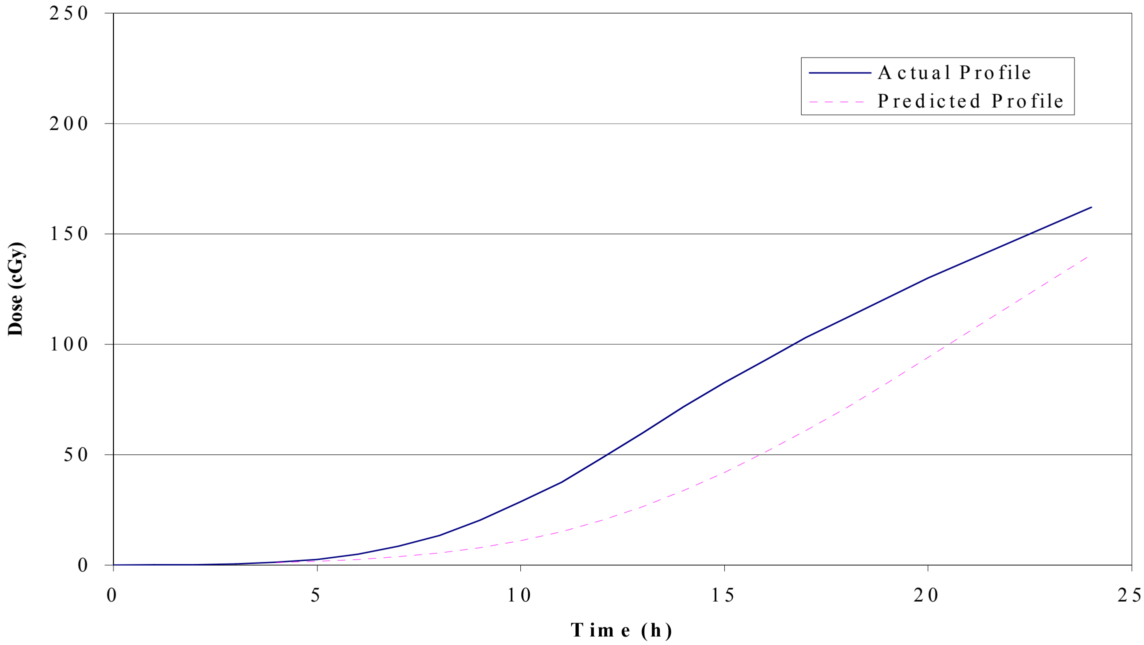

Figure 12. Predicted dose-time profile at 3 hours (or 0.3% of dose at 24 hours) into November 22, 2001 SPE.

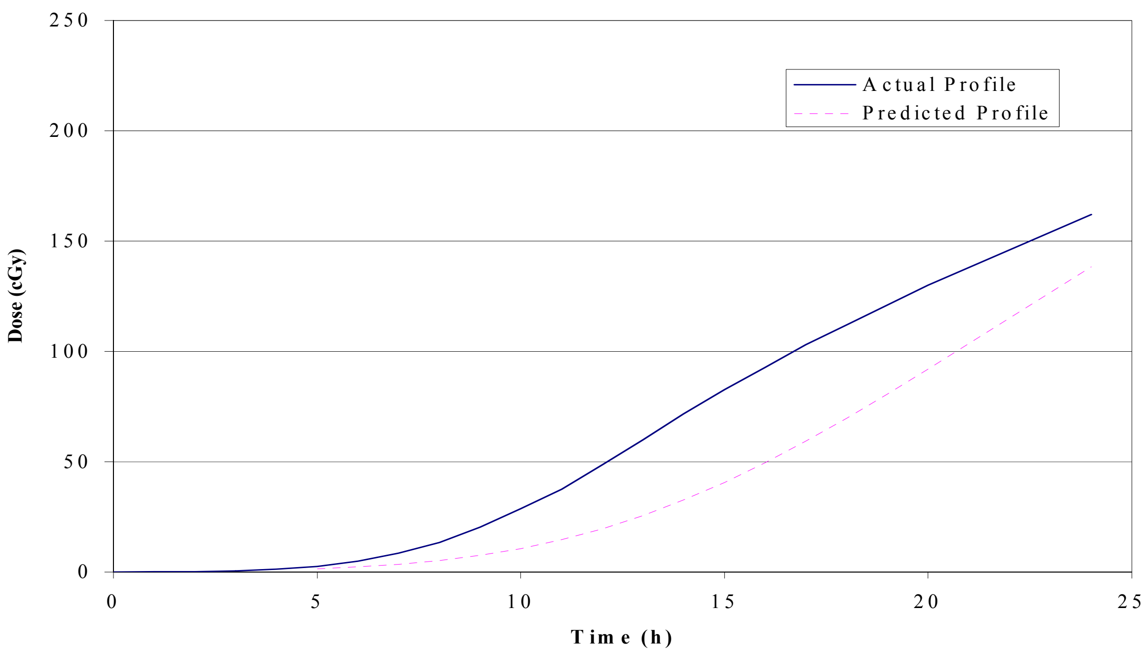

Figure 13. Predicted dose-time profile at 4 hours (or 0.8% of dose at 24 hours) into November 22, 2001 SPE.

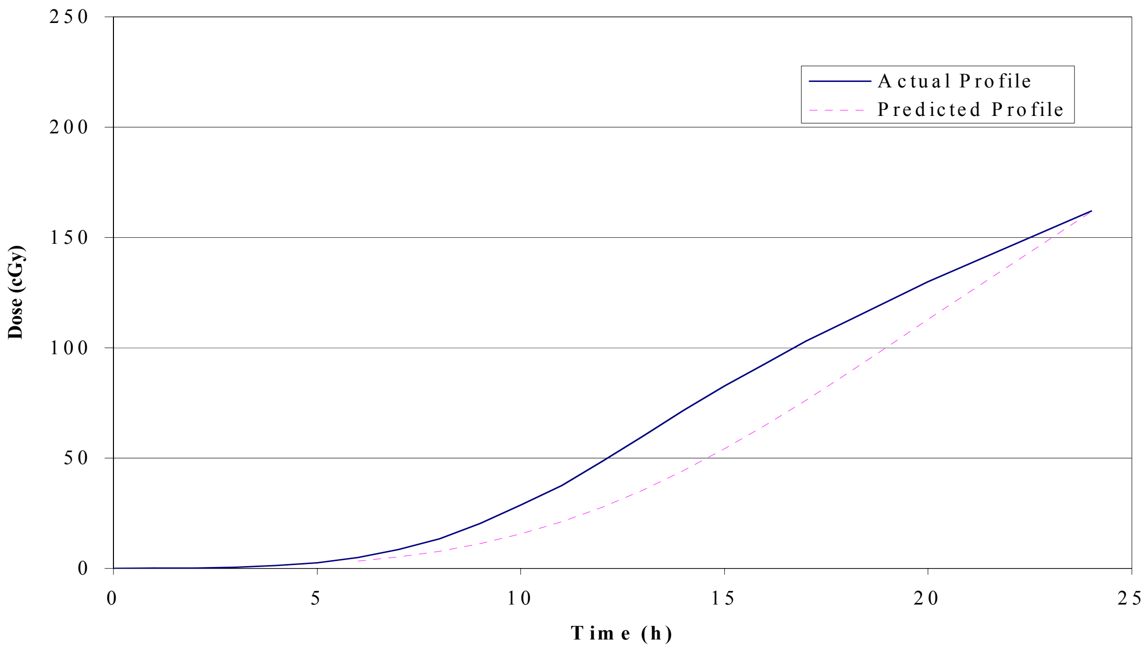

Figure 14. Predicted dose-time profile at 5 hours (or 1.6% of dose at 24 hours) into November 22, 2001 SPE.

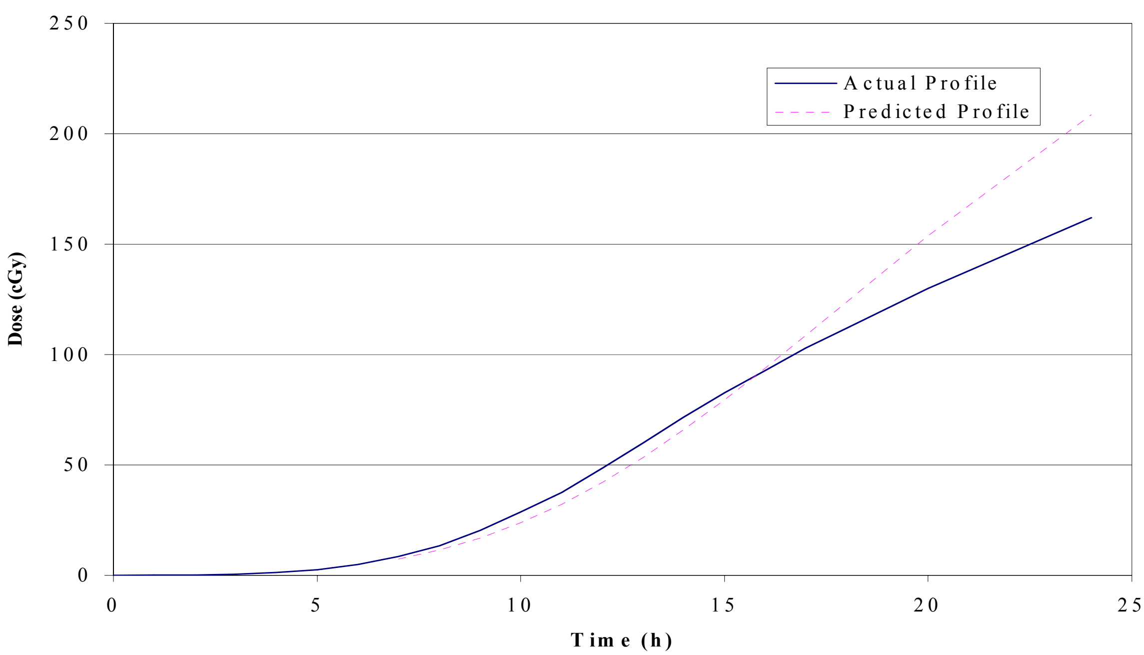

Figure 15. Predicted dose-time profile at 6 hours (or 3.0% of dose at 24 hours) into November 22, 2001 SPE.

4. CONCLUSIONS

Dose-time profiles for absorbed dose in water due to SPE protons have been predicted for the September 24, 2001, November 4, 2001, and November 22, 2001, SPEs. Dose rate values at one or two hours into the events have been used to categorize new events (that is, to place a new event in a group of similar, historical SPEs). Dose values from early in the events have been used with Weibull and Gompertz growth curves to make forecasts of future dose out to 120 hours into the event.

Forecasts for the September 24, 2001 SPE require further investigation as they consistently predict only 60% of the true asymptotic dose for the event. Calculated dose rates early in the event place this event in group 2 while the asymptotic dose falls on the boundary of groups 1 and 2. These results suggest the need for a further refinement of Table 2 categorization criteria. Forecasts for the November 4, 2001 SPE are quite good with a tendency to over-predict dose values at greater forecast times. Forecasts for the November 22, 2001 SPE are also good with a tendency to under-predict at greater forecast times.

Current empirical models do not account for the arrival of interplanetary shocks and the associated increases in dose rates. As the proposed operational implementation of this methodology calls for real-time monitoring of dose and dose rate values, we envision a "rezeroing" of the event at the time of arrival of the interplanetary shock. The time of arrival may be marked by the increase in proton flux and/or the associated increase in dose rate. These results are encouraging with regards to the development of a real-time, event-triggered, advanced warning system.

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